

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

FINAL TECHNICAL REPORT

to

National Aeronautics and Space Administration

from

**The Regents of the University of California
University of California, Los Angeles**

" ORBITAL STUDIES OF LUNAR MAGNETISM "

NGR-05-007-351

July 1, 1972 - April 30, 1982



**Paul J. Coleman, Jr., Principal Investigator
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, CA 90024**

**(NASA-CR-169030) ORBITAL STUDIES OF LUNAR
MAGNETISM Final Technical Report, 1 Jul.
1972 - 30 Apr. 1982 (California Univ.) 14 p
HC A02/MF A01 CSCI 03B**

N82-27268

**Unclass
G3/91 28068**

Report Prepared by

**Malcolm G. McLeod
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, CA 90024**

May, 1982

TABLE OF CONTENTS

	<u>Page</u>
Introduction.	1
Limitations of Present Lunar Magnetic Maps.	1
Optimal Processing of Satellite-Derived Magnetic Anomaly Data	2
Studies of Crustal and Core Geomagnetism.	4
Lunar Remanent Magnetization.	4
Induced Lunar Magnetization	6
Recommendation for Further Research	7
References for Sections 2 through 8	8
Publications on Research Supported by this Grant.	10
Dissertations on Research Supported under this Grant.	12

1. INTRODUCTION

The major objectives of our lunar studies have been to determine the origin and history of the field that produced the remanent magnetism on the moon, and to obtain information on the history and present state of the lunar crust. In previous years we have concentrated on the production of maps of the lunar magnetic field and interpretation of the data represented by the maps. During the past year, we studied various approaches to the determination of mathematical representations of planetary magnetic fields from satellite surveys of the fields.

The main emphasis of our research effort during the past year has been on determining methods for the optimal processing of satellite-derived magnetic anomaly data. The motivation for undertaking this effort was not simply the expectation of being able to make modest improvements in our lunar maps, but rather the expectation of being able to produce vastly superior maps and models of the lunar magnetic field with respect to accuracy and spatial coverage, and of being able to describe this field statistically for comparison with the geomagnetic field.

The longer-term objective is knowledge of the characteristics of the induced and remanent magnetism of bodies in the solar system as well as the planetary dynamo magnetic fields of these bodies.

Questions of a fundamental nature exist regarding the Moon's crustal magnetic field. Most importantly, the origin of the field that produced the crustal magnetization remains unknown. Specification of its origin would have implications for the early history of the solar system as well as that of Moon. Although near-surface magnetic field measurements are available only for Earth and Moon, it seems likely that crustal magnetization is characteristic of all the silicate planetary bodies in the solar system. Thus the development of methods for the quantitative description of crustal magnetic fields is a task of significance for future planetary exploration. The modelling of the lunar field with equivalent point sources, as suggested herein, is a way to succinctly describe the crustal lunar field. The magnetic field at various altitudes can be readily computed from such a model and represented by contour maps. Thus this model is an important first step toward the ultimate goal of understanding the processes that have produced the crustal lunar field.

With respect to future lunar and planetary missions, the results of our most recent studies can be used to establish requirements for amplitude and temporal resolutions of the field measurements, establish requirements for the altitude range of the orbits, and identify regions of special interest.

2. LIMITATIONS OF PRESENT LUNAR MAGNETIC MAPS

Correcting for altitude differences among the measurement positions when constructing a magnetic anomaly map from satellite-derived data is normally a nontrivial problem (Bhattacharyya, 1977; Mayhew, 1979; Mayhew et al., 1980). The slow lunar rotation period allows a simpler solution for a subset of the Apollo data. If only data collected during a single lunation over a particular selenographic area are used, the magnetic anomaly map can be defined

on the curved surface of observation of the subsatellite. This approach was followed by Hood et al. (1981). However, it has a number of serious limitations.

- a. Limited selenographic extent. Although data were collected between $\pm 30^\circ$ latitude, only about fifteen percent of this region has been mapped.
- b. Small fraction of available lunar data used. Even for the limited region mapped, only a small fraction of the available data has been used.
- c. Maps not for spherical surface. The field was mapped on the surface defined by the spacecraft orbits. This surface is "wavey" and of varying altitude, and not convenient for upward or downward continuation.
- d. Filtering not optimized.
- e. Error analysis not inherent in the procedure.
- f. Data not in convenient form for statistical studies.

The limitations noted are a direct consequence of the method of data processing chosen. It is nearly impossible to overstate the severity of these limitations; in comparison to what is potentially achievable with respect to accuracy and spatial coverage of lunar magnetic maps and models based on the Apollo data sets, the maps published thus far represent only a crude and primitive beginning.

Because we recognized the serious limitations of these lunar magnetic maps, we initiated a study during 1980 with the objective of determining methods for the optimal processing of satellite-derived magnetic anomaly data. The results of this study represent a considerable advance beyond the methods for planetary magnetic field mapping and modelling that were available at the time our production of lunar maps was initiated. The methods available at that time were essentially the ones used on the first geomagnetic anomaly map, based on POGO satellite data, produced by Regan et al. (1975).

3. OPTIMAL PROCESSING OF SATELLITE-DERIVED MAGNETIC ANOMALY DATA

In the course of a design study concerned with satellite mapping of the crustal magnetic field of the Earth, we undertook to investigate methods by which to optimize the production of a mathematical representation of the field from a dataset acquired with orbiting spacecraft. During a previous reporting period, we initiated an examination of the similarities and differences of the problems of mapping the crustal fields of the Earth and Moon.

Three papers pertinent to both problems, and thus to the general problem of optimal mapping of planetary magnetic fields from orbiting spacecraft, were published during that previous reporting period. In one, McLeod and Coleman (1980a) discussed some of the limitations of geomagnetic field mapping in terms of the power spectra of instrumentation "noise" and of "noise" due to

time varying external current systems relative to the power spectra of the "signal" due to spacecraft motion through the spatially varying geomagnetic field. It was shown how these spectra are related to the achievable resolution for a given spacecraft altitude, and how these spectra influence the optimal data processing procedure. The second paper, McLeod and Coleman (1980b), is concerned with the statistical description of the geomagnetic field by means of spherical harmonic power spectra, with numerical values of these spectra for the Earth, and with statistical field models that would produce the observed spectra. This paper also contains a discussion of the relation between spherical harmonic power spectra and great circle Fourier power spectra for a circular orbit. In the third paper, McLeod (1980) derives orthogonality relations used in McLeod and Coleman (1980b). These papers are relevant not only to geomagnetic field mapping, but also to mapping the magnetic fields of the moon and other planets.

During that previous reporting period, we presented a paper based on these three publications at the NASA Geodynamics Program review at GSFC, January 26-29, 1981 (McLeod and Coleman, 1981).

During the current reporting period, we continued our studies of planetary magnetic field modelling and mapping. We anticipate that the results of these efforts will find application not only in processing satellite-derived magnetic anomaly data for the Moon, Earth, and other planets, but also in processing aeromagnetic data (for Earth) of much shorter wavelength.

A paper detailing the results of these studies has been completed and accepted for publication (McLeod, 1982a). The paper contains an analysis of the data processing method used by Mayhew et al. (1980) on POGO satellite data over Australia. It is shown that the data processing method used by Mayhew et al. is approximately equivalent to filtering the data to retain only a specific region of the two-dimensional frequency plane. The filter is reasonably close to optimal with respect to accuracy, though some possible improvements are suggested. The analysis makes use of the concept of two-dimensional spatial power spectra and the ideas of Wiener (1949) as discussed by Davenport and Root (1958). Errors remaining after the data processing are discussed, and the analysis indicates how to estimate these errors. The techniques used can be carried over to the problem of lunar magnetic field modelling and mapping. The studies indicate that the basic principles used by Mayhew et al. for crustal geomagnetic field modelling and mapping appear to be most efficient for modelling and mapping the lunar field; however, a number of changes in the detailed methods are necessary and desirable.

A direct harmonic analysis of the data would be impractical for processing the data obtained from a low altitude satellite such as Apollo or Magsat. Harmonic analysis, using methods discussed by McLeod (1982a), can be a useful technique for statistical studies of the lunar magnetic field.

During this reporting period, Dr. McLeod attended two scientific meetings devoted to geodynamics and geomagnetism and made presentations related to the optimal processing of satellite-derived magnetic anomaly data at each meeting. Abstracts of the presentations (McLeod, 1982c,d) were published in the proceedings of these meetings. An abstract (McLeod, 1982e) for a presentation scheduled to be made at the spring AGU meeting in Philadelphia will be published in the May 4, 1982 issue of EOS.

4. STUDIES OF CRUSTAL AND CORE GEOMAGNETISM

Two other papers completed during this reporting period (McLeod, 1981, 1982b) deal with the general subject of geomagnetism as related to both the core and the crust. Besides the immediate scientific value of these studies, the mathematical methods employed are relevant to the study of other planetary fields, including the lunar field.

The first paper (McLeod, 1981) is concerned with geomagnetic variations having (apparent) periods from 13 to 30 years as reported by Ailredge (1977), who has argued that the origin of these signals must be found in the core of the Earth rather than outside the Earth. It is shown in this paper that a portion of these geomagnetic variations (perhaps most of the variations) might well be due to geomagnetic signals of much longer period, originating in the core, that appear to have periods of 13 to 30 years because of an artifact of the data processing. Much of the remainder of these variations could well be of external origin. A superior method for processing these data is suggested in the paper.

Also in this first paper, the background spectra of the geomagnetic field (i.e., with "lines" in the spectra removed) reported by Courtillot and Le Mouél (1976) for the period range 10 years to 2 months are discussed. These spectra are approximately of the $(1/f^2)$ type, as are the geomagnetic spectra for the vastly different period range 4 hours to 5 minutes reported by Campbell (1976) and discussed by McLeod and Coleman (1980b). It is noted that if Campbell's spectra are extrapolated to the period range investigated by Courtillot and Le Mouél, an extrapolation over nearly 3 decades, the two spectra agree numerically (approximately). It is further noted that this $(1/f^2)$ spectrum is the spectrum corresponding to the well-known random walk, or "drunkard's walk."

The second paper (McLeod, 1982b) is concerned with the crustal geomagnetic field and the statistical description of this field by means of spatial power spectra. Two-dimensional Fourier spatial power spectra of equivalent magnetization values for a region that includes a large portion of the western United States are presented. The magnetization values were determined by inversion of POGO satellite data, assuming a 40 km thick magnetic crust, and were located on an 11×10 array, 300 km grid spacing. The spectra appear to be in good agreement with values of the crustal geomagnetic field spatial power spectra given by McLeod and Coleman (1980b) and with the crustal field model given by Serson and Hannaford (1957). The spectra show evidence of noise at low frequencies in the direction along the satellite orbital track (N-S), indicating that for this particular data set, additional filtering would probably be desirable. These findings illustrate the value of two-dimensional spatial power spectra both for describing the geomagnetic field statistically and for diagnosing possible noise sources.

5. LUNAR REMNANT MAGNETIZATION

During a previous reporting period, the analysis of Apollo 15 and 16 subsatellite magnetometer data was extended as one element of a study of the nature and origin of lunar crustal magnetization. This work was supported with funds from NASA grant NSG 7020 LS, the University of Arizona, C. P. Sonett, Principal Investigator, as well as funds from this grant, and performed in collaboration with L. L. Hood at Arizona (Hood et al., 1981).

Correlations of mapped anomalies (Hood et al., 1981a) with surface geologic units continue to indicate that the most strongly magnetized materials may not be deep seated in the crust as expected if their magnetization was acquired by slow cooling in the presence of a steady magnetic field. The least ambiguous correlations are found for relatively surficial units such as the Fra Mauro Formation and the Reiner Gamma swirls (Hood, 1980b). A second example of a magnetic anomaly maximum detected with the subsatellite magnetometers over an area dominated by swirl markings was found near crater Ellerman. Although the radial field amplitude is less than 2 gammas (1 gamma = 10^{-5} G) at 87 km above the surface, an approximate scaling for altitude differences indicates that the source dipole moment is comparable to or larger than that of other anomalies detected with both subsatellites including the Reiner Gamma anomaly and the Van de Graaff-Aitken anomalies. This concentration of swirls is located within 5° of the Crisium antipode raising to at least four the proposed number of young large impact basins that are nearly antipodal to concentrations of swirls and strong magnetic anomalies detected by both magnetometers and charged-particle instruments on board the Apollo subsatellites.

The Fra Mauro Formation is Imbrium basin ejecta. There is independent evidence that areas peripheral to other large impact basins are also magnetized. If the swirls are produced by either meteoroid or cometary impacts as has been suggested, then it remains possible that all observed anomalies are associated with impact-generated surface materials.

A method for distinguishing between local surface magnetizing fields such as may have been produced during impacts and a large-scale or global magnetizing field (Srunka, 1977; Gold and Soter, 1976) and a large-scale or global magnetizing field involves estimating the directions of the bulk magnetization of relatively strongly magnetized and isolated magnetic anomaly sources using the subsatellite vector magnetometer data. In a previous study (Hood et al., 1978) that was limited primarily to the Van de Graaff-Aitken region on the south-central far side, it was found (a) nearby sources are generally magnetized in very different directions; (b) the number of north-south oriented vectors is depleted relative to the number of east-west and radially oriented vectors; and (c) the inferred magnetization directions are otherwise nearly random. Assuming that these properties were repeated elsewhere on the moon, several interpretations were suggested. First, the negligible lunar magnetic dipole moment (Russell et al., 1974) was explained as due to the inferred lack of directional coherence for the magnetization rather than as a consequence of global crustal magnetization along dipolar field lines as earlier suggested (Runcorn, 1975). Second, the north-south depletion of the magnetization intensity was considered to represent an observational constraint that did not favor purely local surface origins of the magnetizing field. An exception was meteoritic or cometary impact processes that might tend to amplify the weak solar wind magnetic field which, on the average, is parallel to the lunar equatorial plane.

During the previous reporting period, additional maps of the vector components of the crustal magnetic field became available with low-altitude coverage exceeding that of older maps by a factor of about ten (Hood et al., 1981a). However, even these maps are of very limited selenographic extent, covering only about fifteen percent of the region for which data are available, as

indicated in a previous section. Thus further improvements in selenographic mapping and modelling would be very valuable.

Bulk directions of magnetization were estimated for sources of the strongest and most isolated magnetic anomalies apparently associated with exposed remnants of the Fra Mauro Formation, and a consolidation of swirls near crater Ellerman. A total of twenty-five directions of magnetization excluding the Van de Graaff-Aitken region have thus far been estimated for sources that are widely distributed in longitude but that are confined latitudinally by the near-equatorial orbits of the Apollo subsatellites. The results again show that adjacent sources are, in general, magnetized in very different directions. This has already been documented for the important special case of the Fra Mauro anomalies (Hood, 1980b). A further result is that the pole positions of a magnetizing dipole assumed to be centered in the moon correspond to these twenty-five vectors are not clustered in any discernible manner. This finding contrasts with that of Runcorn (1979) who found a significant clustering of pole positions corresponding to the bulk directions of magnetization inferred for the Van de Graaff-Aitken region. These results were presented to the Twelfth Lunar and Planetary Science Conference (Hood et al., 1981b).

In addition to the apparent absence of directional evidence for a global lunar magnetizing field, there is now the constraint imposed by the relatively small maximum size of the lunar metallic core radius as estimated from a variety of geophysical measurements. In particular, the most recent upper limit from magnetic sounding data is about 360 km (Hood et al., 1981b). To produce a magnetic field at the lunar surface with an amplitude of order 1 G as required by returned sample studies (14), the field at the surface of a 360 km core must exceed 100 G. For comparison, the corresponding field at the surface of the terrestrial core is about 5 G. Final evidence from orbital data for magnetic fields generated by impact processes would come in the form of a clear association of a mapped anomaly with a young (< 3 b.y. old) surface geological unit. Reiner Gamma is an obvious candidate but photogeologic considerations and the tendency for other swirls to be concentrated near the antipodes of large, young impact basins require a cautious interpretation of these features (Hood, 1980a).

6. INDUCED LUNAR MAGNETIZATION

During a previous reporting period, Apollo 15 and 16 subsatellite fluxgate magnetometer data were analyzed for all intervals in which the moon was in the lobes of the geomagnetic tail to obtain an improved estimate of the average magnitude of the induced dipole moment of the moon. Nontail lobe intervals were excluded by an examination of particle data recorded simultaneously on the subsatellite and on the moon and by a comparison of the magnetic field strength observed with that expected for the solar wind conditions prevailing during the measurements. The surface magnetometer data were used to minimize effects due to temporal changes in the external field. The resulting set of estimates, while smaller than previous sets, has a smaller spread and yields an induced magnetic moment of -4.23×10^{22} Gauss-cm³ per Gauss of applied field, corresponding to a G-factor of $0.08 \pm .011$.

These results, reported to the Twelfth Lunar and Planetary Science Conference, do not place strong constraints on the conductivity of the lunar core. We would detect the observed effects as long as the core conductivity was greater than about 10 mho/m. If the outer, cooler layers of the moon, that are at temperatures below the effective Curie point, contain little or no free iron, then these measurements are consistent with the presence of a conducting core whose radius is slightly larger than 400 km. If these outer layers of the moon contain significant amounts of free iron, and hence exhibit the paramagnetism expected in such a situation, the core size could be ever greater.

7. RECOMMENDATION FOR FURTHER RESEARCH

The study of the optimal processing methods for satellite-derived magnetic anomaly data was motivated by the existence of serious limitations in the existing maps of the lunar field as published by Hood et al. (1981). These limitations are a result of the method of data processing used, so that while data were collected between $\pm 30^\circ$ latitude, only about fifteen percent of this area has been mapped. The maps are not for a spherical surface but for an undulating surface defined by the spacecraft orbits for a single lunation. It is believed that use of the methods described by McLeod (1982a) could result in an improvement in these maps by about an order of magnitude in both accuracy and spatial coverage. The resulting maps would be for a spherical surface, convenient for use in statistical studies, and would constitute a major improvement over existing maps and models of the lunar field.

The general plan of the work should be as follows:

1. Survey the data coverage of the UCLA Apollo magnetometer measurements.
2. Filter the data by (partial) orbits to remove the lowest frequencies. Only data from the lunar wake should be used.
3. Compute sets of normal equations arising from the least squares problem associated with fitting the measured field with the field due to equivalent point monopole sources, as discussed by McLeod (1982a). Northbound and southbound orbits should be treated separately.
4. Solve the normal equations for various regions and combine results with attention to overlapping.
5. Compute the resulting distribution of monopole sources on a finer grid with spatial filtering for input to contouring program.
6. Produce various two-dimensional maps from these results.
7. Subtract the computed values from selected samples of measured orbital data to determine measurement error; compute power spectra of the error and use this computation to estimate errors of the previously computed maps.
8. Compute the spherical harmonic spectrum of the resulting source distributions.

Some experimentation would be necessary to determine the optimal point source grid spacing, and the optimal filtering for steps 2 and 5.

8. REFERENCES FOR SECTIONS 2 THROUGH 8

- Allredge, L. R., Geomagnetic variations with periods from 13 to 30 years, J. Geomag. Geoelectr., 29, 123-135, 1977.
- Bhattacharyya, B. K., Reduction and treatment of magnetic anomalies of crustal origin in satellite data, J. Geophys. Res., 82, 3379-3390, 1977.
- Campbell, W. H., An analysis of the spectra of geomagnetic variations having periods from five minutes to four hours, J. Geophys. Res., 81, 1369-1390, 1976.
- Courtillet, V., and J. L. Le Mouél, On the long period variations of the Earth's magnetic field from 2 months to 20 years, J. Geophys. Res., 81, 2941-2950, 1976.
- Davenport, W. B., Jr., and W. L. Root, Random Signals and Noise, McGraw-Hill, New York, 1958.
- Gold, T., and S. Soter, Cometary impact and the magnetization of the moon, Planet. Space Sci., 24, 45, 1976.
- Hood, L. L., Cometary collisions on the moon and Mercury, Nature, 287, 86, 1980a.
- Hood, L. L., Bulk magnetization properties of the Frau Mauro and Reiner Gamma formations, Proc. 11th Lunar Planet. Sci. Conf., 3, 1879-1896, 1980b.
- Hood, L. L., C. T. Russell, and P. J. Coleman, Jr., The magnetization of the lunar crust as deduced from orbital surveys, Proc. 9th Lunar Planet. Sci. Conf., 3, 3057-3078, 1978.
- Hood, L. L., C. T. Russell, and P. J. Coleman, Jr., Contour maps of lunar remanent magnetic fields, J. Geophys. Res., 86, 1055-1069, 1981a.
- Hood, L. L., C. P. Sonett, F. Herbert, S. Cantrell, and L. L. Smith, The deep lunar electrical conductivity profile: An experimental upper limit on the radius of a metallic core (Abstract), Lunar and Planetary Science XII, Part 2, 457, March 16-20, 1981b.
- Mayhew, M. G., Inversion of satellite magnetic anomaly data, J. Geophys., 45, 119-128, 1979.
- Mayhew, M. A., B. D. Johnson, and R. A. Langel, An equivalent source model of the satellite altitude magnetic anomaly field over Australia, Earth Planet. Sci. Lett., 51, 189-198, 1980.
- McLeod, M. G., Orthogonality of spherical harmonic coefficients, Phys. Earth Planet. Int., 23, P1-P4, 1980.

- McLeod, M. G., A note on the secular variation of the geomagnetic field, (IGPP Pub. No. 2272), Phys. Earth Planet. Int., in press, 1981.
- McLeod, M. G., Optimal processing of satellite-derived magnetic anomaly data (IGPP Pub. No. 2295), Phys. Earth Planet. Int., in press, 1982a.
- McLeod, M. G., Crustal geomagnetic field: Two-dimensional intermediate wavelength spatial power spectra (IGPP Pub. No. 2308), Submitted to Phys. Earth Planet. Int., 1982b.
- McLeod, M. G., Filtering satellite-derived magnetic anomaly data (Abstract), Fourth Annual NASA Geodynamics Conference, GSFC, January 26-29, 1982c.
- McLeod, M. G., Optimal filtering of satellite-derived magnetic anomaly data, (Abstract), Workshop on Geomagnetism, sponsored by U.S. Geol. Survey, Golden, CO, April 13-15, 1982d.
- McLeod, M. G., Optimal filtering of satellite-derived magnetic anomaly data (Abstract), to be presented at Spring AGU meeting, Philadelphia, PA, EOS (Trans. Am. Geophys. U.), 1982.
- McLeod, M. G., and P. J. Coleman, Jr., Geomagnetic field mapping from a satellite: Spatial power spectra of the geomagnetic field at various satellite altitudes relative to natural noise sources and instrument noise, Phys. Earth Planet. Int., 23, 222-231, 1980a.
- McLeod, M. G., and P. J. Coleman, Jr., Spatial power spectra of the crustal geomagnetic field and core geomagnetic field, Phys. Earth Planet. Int., 23, P5-P19, 1980b.
- McLeod, M. G., and P. J. Coleman, Jr., Spatial power spectra of the geomagnetic field (Abstract), Third Annual NASA Geodynamics Conference, GSFC, January 26-29, 1981.
- Regan, R. D., J. C. Cain, and W. M. Davis, A global magnetic anomaly map, J. Geophys. Res., 70, 794-802, 1975.
- Runcorn, S. K., On the interpretation of lunar magnetism. Phys. Earth Planet. Int., 10, 327-335, 1975.
- Runcorn, S. K., An iron core in the moon generating an early magnetic field? Proc. 10th Lunar Planet. Sci. Conf., 3, 2325-2333, 1979.
- Russell, C. T., P. J. Coleman, Jr., and G. Schubert, Lunar magnetic field: Permanent and induced dipole moment, Science, 188(4160), 825-826, 1974.
- Serson, P. H., and W. L. W. Hannaford, A statistical analysis of magnetic profiles, J. Geophys. Res., 62, 1-18, 1957.
- Srnka, L. J., Spontaneous magnetic field generation in hypervelocity impacts, Proc. 8th Lunar Sci. Conf., 1, 785-792, 1977.

Wiener, N., Extrapolation, Interpolation, and Smoothing of Stationary Time Series. John Wiley, New York, 1949.

9. PUBLICATIONS ON RESEARCH SUPPORTED BY THIS GRANT.

Anderson, K. A., R. P. Lin, R. E. McGuire, J. E. McCoy, C. T. Russell, and P. J. Coleman, Jr., Lunar magnetization features associated with Rima Sirsalis. Earth Planet. Sci. Lett., 34, 141-151, 1977.

Coleman, P. J., Jr., and C. T. Russell, The remanent magnetic field of the Moon. Phil. Trans. R. Soc., London A, 285, 489-507, 1977.

Hood, L., Sources of lunar magnetic anomalies and their bulk directions of magnetization (Abstract). Lunar and Planetary Science XII, Part 2, 457, March 16-20, 1981.

Hood, L., Sources of lunar magnetic anomalies and their bulk directions of magnetization. Proc. 12th Lunar Planet. Sci. Conf., 1, 817-830, 1981.

Hood, L. L., P. J. Coleman, Jr., C. T. Russell, and D. E. Wilhelms, Lunar magnetic anomalies detected by the Apollo subsatellite magnetometers. Phys. Earth Planet. Int., 20, 291-311, 1979.

Hood, L. L., P. J. Coleman, Jr., and D. E. Wilhelms, The moon: Sources of the crustal magnetic anomalies, Science, 204, 53, 1979.

Hood, L. L., P. J. Coleman, Jr., and D. E. Wilhelms, Lunar nearside magnetic anomalies. Proc. 10th Lunar Planet. Sci. Conf., 3, 2235-2257, 1979.

Hood, L. L., C. T. Russell, and P. J. Coleman, Jr., Evidence for a non-random magnetization of the moon. Geophys. Res. Lett., 5, 305-308, 1978.

Hood, L. L., C. T. Russell, and P. J. Coleman, Jr., The magnetization of the lunar crust as deduced from orbital surveys. Proc. 9th Lunar Planet. Sci. Conf., 3, 3057-3078, 1978.

Hood, L. L., C. T. Russell, and P. J. Coleman, Jr., Contour maps of lunar remanent magnetic fields. J. Geophys. Res., 86, 1055-1069, 1981.

Hood, L. L., and G. Schubert, Lunar magnetic anomalies and surface optimal properties, Science, 208, 49, 1980.

Lichtenstein, B. R., P. J. Coleman, Jr., and C. T. Russell, A comparison of contour maps derived from independent methods of measuring lunar magnetic fields. Proc. 9th Lunar Planet. Sci. Conf., 3, 3079-3092, 1978.

Lin, R. P., K. A. Anderson, J. E. McCoy, and C. T. Russell, Observations of magnetic merging and the formation of the plasma sheet in the Earth's magnetotail. J. Geophys. Res., 82, 2761-2773, 1977.

McLeod, M. G., Orthogonality of spherical harmonic coefficients. Phys. Earth Planet. Int., 23, P1-P4, 1980.

- McLeod, M. G., A note on the secular variation of the geomagnetic field (IGPP Pub. No. 2272), Phys. Earth Planet. Int., in press, 1981.
- McLeod, M. G., Optimal processing of satellite-derived magnetic anomaly data (IGPP Pub. No. 2295), Phys. Earth Planet. Int., in press, 1982.
- McLeod, M. G., Crustal geomagnetic field: Two-dimensional intermediate wavelength spatial power spectra (IGPP Pub. No. 2308), Submitted to Phys. Earth Planet. Int., 1982.
- McLeod, M. G., Filtering satellite-derived magnetic anomaly data (Abstract). Fourth Annual NASA Geodynamics Conf., GSFC, January 26-29, 1982.
- McLeod, M. G., Optimal filtering of satellite-derived magnetic anomaly data. (Abstract). Workshop of Geomagnetism, sponsored by U.S. Geol. Survey, Golden, CO, April 13-15, 1982.
- McLeod, M. G., Optimal filtering of satellite-derived magnetic anomaly data (Abstract). Presented at Spring AGU Meeting, Philadelphia, CA. EOS (Trans. Am. Geophys. U.), 1982.
- McLeod, M. G., and P. J. Coleman, Jr., Spatial power spectra of the crustal geomagnetic field and core geomagnetic field. Phys. Earth Planet. Int., 23, P5-P19, 1980.
- McLeod, M. G., and P. J. Coleman, Jr., Geomagnetic field mapping from a satellite: Spatial power spectra of the geomagnetic field at various satellite altitudes relative to natural noise sources and instrument noise. Phys. Earth Planet. Int., 23, 222-231, 1980.
- McLeod, M. G., and P. J. Coleman, Jr., Spatial power spectra of the geomagnetic field (Abstract). Third Annual NASA Geodynamics Conference, GSFC, January 26-29, 1981.
- Metzger, A. E., R. P. Lin, and C. T. Russell, On a correlation between surface remanent magnetism and chemistry for the lunar frontside and limbs. Proc. 8th Lunar Sci. Conf., 1, 1187-1190, 1977.
- Runcorn, S. K., and P. J. Coleman, Jr., Space: A new phase? Nature, 265(5591), 197-199, 1977.
- Russell, C. T., P. J. Coleman, Jr., and B. E. Goldstein, Measurements of the lunar induced magnetic moment in the geomagnetic tail: Evidence for a lunar core? Proc. 12th Lunar Planet. Sci. Conf., 1, 831-836, 1981.
- Russell, C. T., P. J. Coleman, Jr., and G. Schubert, On deducing the magnetization of the lunar surface from orbital surveys. Phys. Earth Planet. Int., 13, 386-390, 1977.
- Russell, C. T., H. Weiss, P. J. Coleman, Jr., L. A. Soderblom, D. E. Stuart-Alexander, and D. E. Wiethelms, Geologic-magnetic conditions on the moon: Apollo subsatellite results. Proc. 8th Lunar Sci. Conf., 1, 1171-1185, 1977.
- Weiss, H., and P. J. Coleman, Jr., The moon's permanent magnetic field: A cratered shell model. The Moon, 16, 311-315, 1977.

Weiss, H., L. L. Hood, and P. J. Coleman, Jr., Extended analysis of the cratered shell model of the moon's permanent magnetic field. Proc. 8th Lunar Sci. Conf., 1, 757-766, 1977.

Weiss, H., C. T. Russell, B. R. Lichtenstein, and P. J. Coleman, Jr., Solar wind interaction with the moon: Enhanced magnetic fluctuations at low altitudes. Geophys. Res. Lett., 5, 592-594, 1978.

10. DISSERTATIONS ON RESEARCH SUPPORTED UNDER THIS GRANT

Hood, L. L., Lunar Crustal Magnetic Anomalies Detected by the Apollo Sub-satellite Magnetometers, Ph.D. Dissertation, University of California, Los Angeles, California, 1979.

Weiss, H., Lunar Magnetism and Plasma Interactions, Ph.D. Dissertation, University of California, Los Angeles, California, 1979.